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ABSTRACT

An experimental investigation of adiabatic, two-phase, frictional pressure drop was conducted using 6-port and 14-port microchannels with hydraulic diameters of 1.54 mm and 1.02 mm, respectively. Two-phase fluid flow conditions include mass fluxes from 50 to 440 kg/s.m^2, qualities between 0 and 1, and saturation temperatures for working fluids carbon dioxide at 15ºC, ammonia at 35ºC, and R245fa at 40ºC. Experimentation indicates that two-phase pressure drop is dependent upon the average kinetic energy density of the flow, hydraulic diameter, and friction factor, allowing the single-phase pressure drop equation with a modified homogeneous fluid density to predict two-phase pressure drop.

1. INTRODUCTION

Popularity of microchannel heat exchangers using extruded aluminum, multi-port tubes has grown recently due to their potential for increased performance and cost reduction. As industries attempt to reduce size and increase efficiency of heat exchangers, microchannels are becoming a common solution in automotive condensers and increasingly in evaporators designed for air conditioning applications. Aluminum microchannel tubes are flat, having several small diameter channels, or ports, with hydraulic diameters typically ranging from 0.5 mm to 2 mm in size. Although called microchannels, implying diameters on order of 1 μm, microchannel port diameters are actually much larger, making the name somewhat misleading. Despite the misnomer, the term microchannel will be used, as commonly accepted in industry, in this particular application as micro refers to the small size of the channels when compared with conventional refrigeration tubing.

The purpose of this article is to increase the basic understanding of pressure drop by presenting the experimental results of an investigation using aluminum microchannels with carbon dioxide, ammonia, and R245fa. Refrigerants in this study were chosen because they represent extremes of liquid and vapor densities that are commonly found in refrigeration systems; carbon dioxide has low liquid and high vapor density, ammonia has low liquid and vapor density, and R245fa has high liquid and low vapor density. While a myriad of correlations predicting pressure drop are already available, these formulas generally apply only to the specific conditions under which they were developed. The results of this study are valuable because they will potentially help achieve a fundamental understanding of pressure drop that will contribute to the future development of a generalized physical model of this phenomenon.

2. LITERATURE REVIEW

In two phase flow, total pressure drop, described by Equation (1), is comprised of three contributing factors denoted by subscripts; a frictional dissipation term (*f*), an acceleration head term (*a*), and a static term due to gravitational effects (*g*).

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\right)_f + \left(\frac{dP}{dz}\right)_a + \left(\frac{dP}{dz}\right)_g \tag{1}$$

In this formula, *dP/dz* is the gradient of pressure in the direction of flow. For the purpose of these experiments, acceleration and gravitational terms can be neglected due to adiabatic conditions and horizontal flow. Frictional pressure drop in two-phase flow is due to the combination of interactions between the fluid and the walls of the tube and between the liquid and vapor phases. While copious correlations to predict two-phase frictional pressure drop exist, these formulas have been developed for specific conditions and no general theory exists to predict the pressure loss due to friction. Unfortunately, these empirical correlations predicting two-phase pressure drop are limited to the range of conditions at which they were developed and often fail spectacularly outside of these regions. Both Payne (2000) and Niño (2002) present excellent examples of correlations developed in both large and small tubes failing when applied to microchannels and different refrigerants.

Many two-phase pressure drop correlations utilize a two-phase multiplier (Φ) defined by Martinelli and Nelson (1948) and Lockhart and Martinelli (1949) which relates the two-phase frictional pressure drop in terms of either single phase liquid or vapor pressure drop. For the purpose of this investigation, a vapor only multiplier is defined in Equation (2) such that

$$\left(\frac{dP}{dz}\right)_f = \Phi_{vo}^2 \left(\frac{dP}{dz}\right)_{vo} \tag{2}$$

where the subscript *vo* indicates that the entire flow in the channel is made up of vapor only. The reason for choosing the vapor only basis is due to Niño (2002) finding that "liquid only" based correlations often fail when applied to small channels due to the Reynolds number dropping to levels below the laminar-turbulent transition range (Re ~ 2300). For typical mass flux ranges, the vapor only basis keeps the Reynolds number above the transition region, resulting in a more consistent reference level for the multiplier. Note that the single-phase pressure gradients are determined by Equation (3) as the following

$$\left(\frac{dP}{dz}\right)_{vo} = f_{vo} \frac{1}{D_h} \frac{G^2}{2\rho_v} \tag{3}$$

where D_h is the hydraulic diameter, G is the mass flux, ρ_v is the vapor density, and f_{vo} is the single phase, turbulent Darcy friction factor determined using the Blausius formula and Reynolds number in Equations (4) and (5), respectively,

$$f_{vo} = \frac{0.316}{\mathrm{Re}^{0.25}} \quad \text{and} \quad \mathrm{Re} = \frac{GD_h}{\mu_v} \tag{4, 5}$$

where μ is the viscosity of the fluid. An important physical interpretation of Equation (3) can be realized by defining the average kinetic energy density in Equation (6) as

$$ke_{avg} = \frac{G^2}{2\rho} \tag{6}$$

which indicates that pressure drop is directly proportional to the inertial forces of the fluid flow.

Two idealized models developed for frictional pressure drop in two-phase flow are the homogeneous and separated flow models. Homogeneous models best describe intermittent and dispersed flows while separated models are used to predict stratified and annular flows. In homogeneous flow, the model assumes that liquid and vapor portions of the flow are mixed together and their velocities are equal. An additional simplification that arises from mixed flow is to consider the homogenous two-phase flow as a single phase with average fluid properties determined by the quality of the mixture. The separated flow model considers the liquid and vapor portions of the mixture to flow separately. In this model, the liquid and vapor may flow at different velocities, but are assumed to have an equal static pressure drop.

Homogeneous pressure drop is described by using Equation (3) and replacing the vapor density (ρ_v) with two-phase density ($\rho_{2\phi}$), or average density, defined in Equation (7) by assuming the two phases are thoroughly mixed

$$\rho_{2\phi} = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l} \right)^{-1} \tag{7}$$

where x is the quality of the fluid and the subscript l indicates the liquid phase. Collier and Thome (1996) utilized a homogeneous flow model for contraction and expansion devices to develop Equation (8), a correlation for pressure drop, which is of the form

$$\Delta P_{C/E} = C \frac{G^2}{2\rho_{2\phi}} \tag{8}$$

where C is a constant that depends on flow conditions and the exact shape of the contraction and expansion sections. This model proposes that the inlet and outlet section pressure drops are correlated to the average kinetic energy density of the flow.

Lockhart and Martinelli (1949) performed experiments that led to a separated flow model proposal based upon two basic postulates. The first states that the static pressure drop for both liquid and vapor phases are the same regardless of the flow pattern as long as the changes of static pressure in the radial direction are not significant. They infer that slug or plug flows are eliminated from consideration. A second postulate states that the sum of the volumes occupied by vapor and liquid at any instant is equal to the total volume of the pipe, which is the mass continuity equation. Lockhart and Martinelli (1949) also developed a parameter (X_{tt}), as shown in Equation (9), which is equal to the square root of the ratio of the liquid to the vapor frictional pressure drop and is commonly used to characterize separated flows.

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.875} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.125} \tag{9}$$

Niño (2002) discusses several of these correlations and finds that none of the existing correlations accurately predict pressure drop of annular flow in microchannels. Consequently, Niño (2002) proposes Equation (10) as a correlation for pressure drop of annular flow.

$$\left(\frac{dP}{dz} \right)_{2\phi-annular} = \Phi_{vo}^2 \left(f_{vo} \frac{1}{D_h} \frac{G^2}{2\rho_v} \right) \tag{10}$$

$$\Phi_{vo}^2 = f\left[\left(X_{tt} + \frac{1}{We_v^{1.3}} \right) \left(\frac{\rho_l}{\rho_v} \right)^{0.9} \right] \tag{11}$$

$$We_v = \frac{x^2 G^2 D}{\rho_v \sigma} \tag{12}$$

In Equations (11), f indicates that the two-phase flow multiplier is a function of the bracketed parameters, We is the Weber number which relates inertial to surface tension forces, and σ is surface tension.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental test section consists of a microchannel and two transition sections that connect the flat microchannel to round 8.9 mm (3/8") tubes common in refrigeration systems. Transition sections also serve as locations for the measurement of system and differential pressure. Two multi-port, rectangular aluminum microchannels were used for conducting pressure drop experiments. Carbon dioxide, ammonia, and R245fa were all studied using adiabatic conditions in 14-port, rectangular microchannel tubes with a hydraulic diameter and cross-sectional area of 1.02±0.01 mm and 15.0±0.01 mm^2, respectively. Only ammonia was also studied in a 6-port tube with a hydraulic diameter of 1.54±0.02 mm and a cross-sectional area of 16.7±0.1 mm^2. Dimensions of the microchannels were measured using digital image processing. This method analyses a digital image of the polished cross-section of a microchannel and essentially counts pixels to determine the area of each channel.

Transition sections, which are machined from aluminum and sealed using O-rings, connect the circular tubes of the flow facility to the flat microchannel tube, allow pressure measurement, and facilitate evacuation of refrigerant to the void fraction tank. Details of transition section design can be found in Payne (2000). The three flow facilities used for experimentation allow mass flux, quality, and saturation temperature of the refrigerants to be controlled precisely. The three facilities were needed to meet the requirements of each refrigerant; carbon dioxide requires a high pressure facility, ammonia requires a facility without copper bearing materials, while R245fa can be used in a facility used for common refrigerants. Details relating to the design and construction of these facilities can be found in Payne (2000), Vollrath (2003), and Wilson (2001) for carbon dioxide, ammonia, and R245fa, respectively. In general, each facility is equipped with identical instrumentation and the corresponding accuracies will apply. Coriolis mass flow meters are used to measure liquid and vapor flow with an accuracy of ±0.10% and ±0.50%, respectively. Pressures were measured using transducers with an accuracy of ±0.25% of full scale. Temperature measurements were obtained using type T thermocouples with an accuracy of ±0.25ºC. Liquid and vapor densities of a refrigerant are calculated using computer programs in which thermodynamic properties are calculated using a function call in terms of temperature and pressure. The precision of quality is found with error propagation analysis, giving the precision for quality to be $x = 0.003x^{-1.193}$. Error decreases as quality increases, allowing qualities above 0.4 to be determined with an error less than 1%.

Pressure drop data was collected for mass fluxes ranging from 50 to 440 $kg/s.m^2$ and qualities from 0 to 1 as described previously. Experimental saturation temperatures were 15ºC for carbon dioxide, 35ºC for ammonia, and 40ºC for R245fa. Once steady-state flow conditions were achieved in the test section, a minimum of twenty data points were recorded and the values were averaged to obtain flow properties and the pressure drop at those conditions. Pressure drop was measured in three separate lengths of microchannel tubing, 1.067 m (42”), 0.610 m (24”), and 0.076 m (3”) to ensure consistency of data and to extrapolate entrance and exit effects.

4. RESULTS AND DISCUSSION

Pressure losses in the entrance and exit were measured by connecting two transition sections with a short, 0.076 m (3”), microchannel section. By plotting the measured pressure drop against the average kinetic energy of the flow a linear relationship is obtained, which corroborates the work of Collier and Thome (1996) described by Equation (8). The constant, *C*, appears to be proportional to the liquid to vapor density ratio; however, insufficient data exists at this time to draw more specific conclusions about this relationship. The linear relation of Equation (8) is consistent with experimental data, with the exception of the highest mass fluxes and qualities, where the correlation slightly over-predicts the pressure losses due to the transition sections. To extrapolate the pressure drop caused by the transition sections, pressure drop measurements in the shortest section were subtracted from a longer section to leave the pressure drop due to a 0.991 m (39”) or 0.533 m (21”) microchannel at a particular quality. Pressure drop was normalized to a length basis and consistency of data between the 0.991 m and 0.533 m sections was observed.

Figures 1 through 3 present the pressure drop per meter, or pressure gradient, of each refrigerant in their respective microchannel plotted against inlet quality. Examining the two-phase pressure drop results reveals several trends. Most notably, as mass flux increases, pressure drop increases related to the square of mass flux. Another easily identifiable trend is that pressure drop increases with quality, with the exception of some very high quality conditions. Starting with a quality of zero, pressure drop can be seen to increase nearly linearly for most of the quality range. Yet, at high qualities the pressure drop begins to depart from the linear relationship, causing a flattening out and even a downward bend of the two-phase pressure drop curve. This departure from a linear relationship is seen most dramatically at high mass fluxes and with refrigerants that have a low vapor density. Consequently, the departure from linearity of the two-phase pressure drop is much greater for R245fa and ammonia than it is for carbon dioxide. This departure can be explained by realizing that two-phase flow contains an interaction between liquid and vapor phases of the flow. Interactions between the two phases result in dissipation of energy, causing a pressure loss across the test section. An example of these interactions exists in wavy annular flow, which consists of liquid waves that extend into the vapor core. Since the vapor in the core of the channel flows more quickly than the surrounding liquid layer, the waves act as obstructions to the vapor flow, and the interactions between the two phases cause an inertial energy loss, realized through a pressure drop. As quality increases towards

1, the thickness of the liquid film on the tube wall thins and the size of the waves decreases. As this process occurs, liquid-vapor interactions decrease and pressure drop gradually departs from the linear relationship that was exhibited at low qualities. For fluids with low vapor densities, the pressure drop can actually decrease in the very high quality range. Detailed descriptions of flow regimes in microchannels are described by Coleman and Garimella (1999).

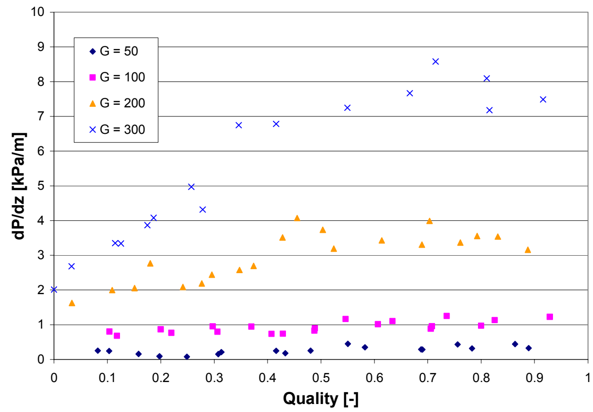

Figure 1: Pressure gradient for carbon dioxide in a 14-port microchannel for given mass flux (G) [kg/s.m^2].

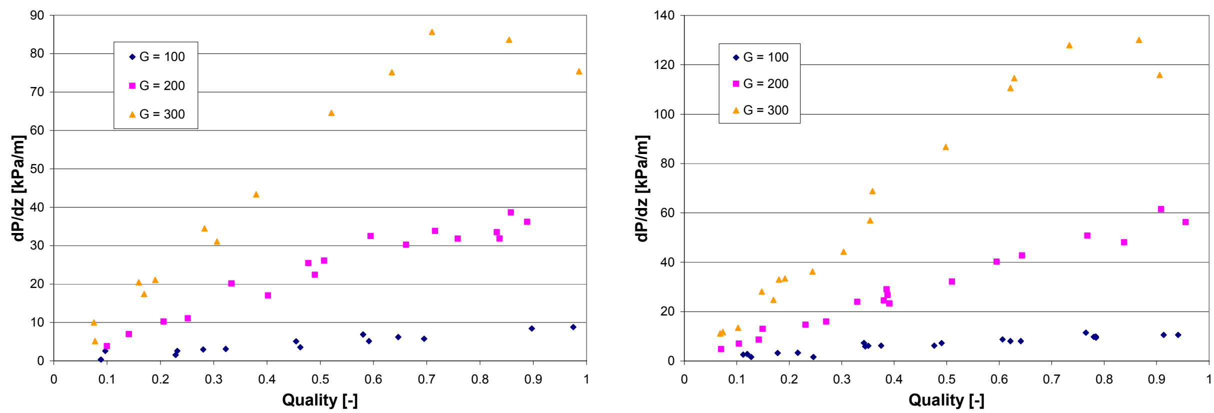

Figure 2: Pressure gradient for ammonia in (left) a 6-port microchannel and (right) a 14-port microchannel for given mass flux (G) [kg/s.m^2].

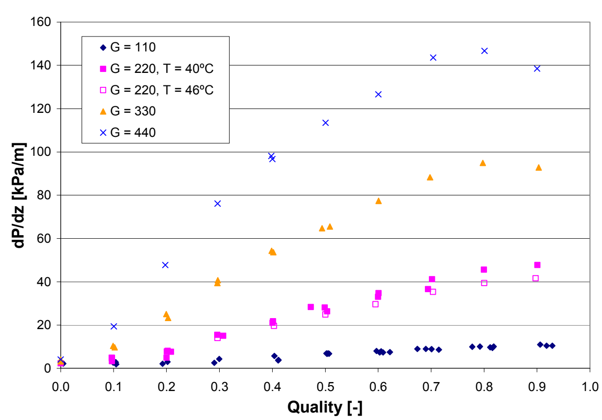

Figure 3: Pressure gradient for R245fa in a 14-port microchannel for given mass flux (G) [kg/s.m^2] and saturation temperature.

Saturation temperature also plays an important role in two-phase pressure drop primarily due to its effect on vapor density. Figure 3 shows experimental results of two-phase pressure drop of R245fa with a mass flux of 220 kg/s.m^2 at two different saturation temperatures. This experimental data confirms that increasing the saturation temperature decreases the two-phase pressure drop. A physical explanation of this phenomenon is that as saturation temperature increases, vapor density also increases. As higher vapor density corresponds to lower pressure drop due to lower relative vapor velocities, increasing the saturation temperature decreases the two-phase pressure drop for that fluid. Each of the three refrigerants studied in this investigation were plotted in Figure 4 for mass flux of about 300 kg/s.m^2 in the 14-port microchannel. By plotting the results in this manner it can be seen that vapor density is inversely related to the two-phase pressure drop of a refrigerant. Additionally, liquid density plays little to no role in determining the magnitude pressure drop as the liquid to vapor density ratio is greater for R245fa than for ammonia, yet ammonia creates a greater pressure drop due to its lower vapor density.

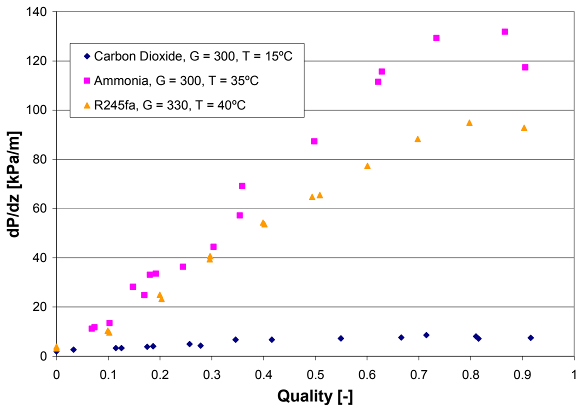

Figure 4: Pressure gradient of the three fluids studied in this investigation in a 14-port microchannel for given mass flux (G) [kg/s.m^2] and saturation temperature.

The average kinetic energy relation was shown by Niño (2002) to provide a correlation for two-phase pressure drop in the intermittent flow regime. Figure 5 shows carbon dioxide, ammonia, and R245fa pressure drop data plotted against the average kinetic energy and divided by hydraulic diameter to collapse the data. Figure 5 also presents the data from this investigation as well as experiments conducted by Niño (2002) using R134a, R410A, and air-water mixtures in both 6 and 14-port microchannels. As can be seen, the average kinetic energy relation collapses the data very well for this diverse range of refrigerants. The average kinetic energy relation loses its significance for correlating pressure drop at the location where the pressure gradient begins decreasing. This is an indication of a change in flow regime from largely intermittent to one with annular flow characteristics.

One caution arises when using experimental data with the average kinetic energy correlation. When a large pressure drop exists, the conditions at the entrance of the test section become different than the conditions at the exit of the test section due to density variations of the vapor phase and quality. Outlet flow conditions were used for all property calculations in these analyses, such as determining the average kinetic energy of a flow, since Jassim (2001) found exit conditions to more accurately predict pressure drop than inlet conditions. Some variation from linearity seen with high values of average kinetic energy may be attributed to using the exit conditions as in actuality the flow in the test section is related to both inlet and exit conditions. For most of the data, the difference between the inlet and outlet property changes is negligible.

As mass flux and quality increase, the flow is less likely to be intermittent and transitions to annular flow. This actuality requires a formulation that will predict two-phase pressure drop in the annular flow regime. Figure 6 shows the annular correlation developed by Niño (2002), which is a function of the two-phase multiplier (Φ_{vo}), plotted against the experimental two-phase flow multiplier for carbon dioxide, ammonia, and R245fa on a log-log plot. It should be noted that the annular two-phase pressure drop correlation attempts only to collapse the data points, not to provide an explicit solution. When viewing the plot, it is apparent that while carbon dioxide does not collapse well with this correlation, ammonia and R245fa collapse reasonably well. Carbon dioxide data appears rather scattered, especially with experimental Φ_{vo} values less than unity. Low values of Φ_{vo} correspond to low qualities and mass flux, and thus the flow will be more likely to be in the intermittent flow regime rather than the annular regime, explaining the inaccuracy of the relation. Figure 6 also shows that the 6-port data is systematically shifted from the 14-port data, which suggests the correlation does not fully account for the effect of hydraulic diameter.

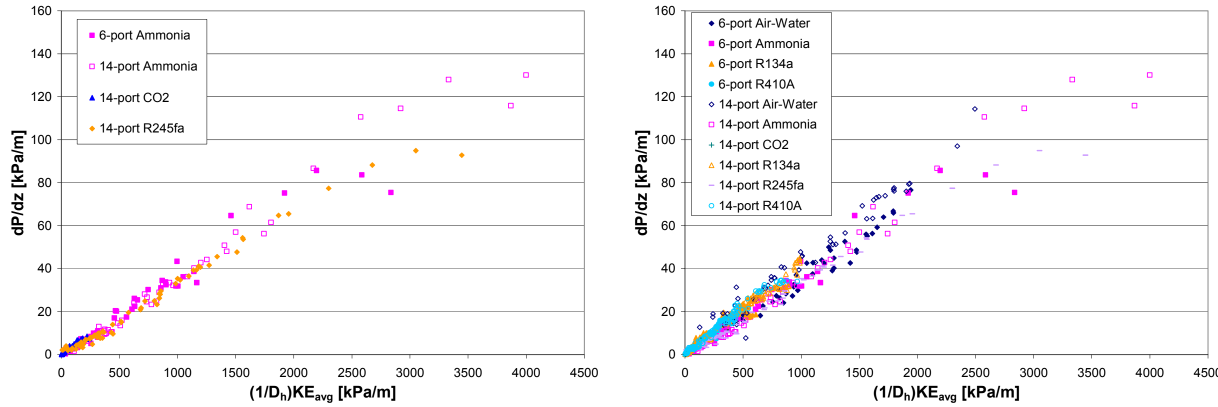

Figure 5: Average kinetic energy relation using (left) carbon dioxide, ammonia, and R245fa as refrigerants and (right) a diverse range of refrigerants including work by Niño (2002) in 6 and 14-port microchannels.

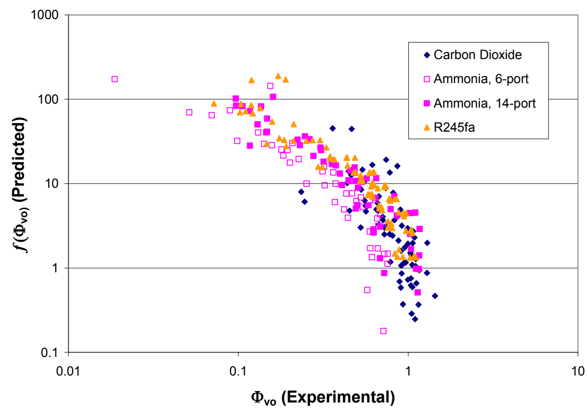

Figure 6: Annular flow correlation for all carbon dioxide, ammonia, and R245fa data collected in experiments plotted on a log-log plot.

5. CONCLUDING REMARKS

Two-phase pressure drop data for two rectangular port microchannel tubes were presented and analyzed in this study. Entrance and exit pressure losses were measured and the average kinetic energy of the flow was correlated to these losses. Carbon dioxide, ammonia, and R245fa were examined in two-phase pressure drop experiments and peak pressure drop was determined to be inversely related to vapor density. The average kinetic energy relation was found to predict pressure drop results well for all refrigerants, but becomes less accurate at very high qualities, especially as mass flux increases and with low vapor density refrigerants. The average kinetic energy relation is significant because it indicates that inertial forces are the greatest contributor to pressure drop. Additionally, fluids with a lower vapor density will generate a greater two-phase pressure drop due to the formulation of average density. A prediction of two-phase pressure drop in the intermittent regime can be achieved using Equation (13),

$$\left(\frac{dP}{dz}\right)_{2\phi-Homogeneous} = 0.035\left(\frac{1}{D_h}\frac{G^2}{2\rho_{2\phi}}\right) \tag{13}$$

where $f_D = 0.035$ is the empirically determined friction factor of the microchannel tubes used in these experiments. Finally, the annular flow relation was found to correlate the two-phase flow multiplier relatively well for ammonia and R245fa, but a discrepancy between 6-port and 14-port results was observed that suggests the correlation does not completely collapse effects of hydraulic diameter. However, the annular low relation does appear to collapse pressure drop data at high mass flows and qualities, conditions where the kinetic energy relation predicts experimental data less accurately.

NOMENCLATURE

C	constant	(-)
D_h	hydraulic diameter	(m)
f	Darcy friction factor	(-)
G	mass flux	(kg s^{-1} m^{-2})
ke	kinetic energy density	(kPa)
dP/dz	pressure gradient	(kPa m^{-1})
ΔP	pressure drop	(kPa)
Re	Reynolds number	(-)
We	Weber number	(-)
x	quality	(-)
X_{tt}	Lockhart-Martinelli parameter	(-)
μ	viscosity	(N s m^{-2})
ρ	density	(kg m^{-3})
σ	surface tension	(N m^{-1})
Φ	two-phase multiplier	(-)

Subscripts

a	acceleration head
avg	average
C/E	contraction and expansion
f	frictional dissipation
g	gravitational effects
l	liquid
v	vapor
vo	vapor only
2ϕ	two-phase

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